

X-ray Detection of SN1994W in NGC 4041?

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ABSTRACT

Optical spectra of SN1994W in NGC 4041 revealed the presence of a dense ($N_e > 10^8 \text{ cm}^{-3}$) circumstellar shell. An observation with the *ROSAT* HRI detected a source, with a luminosity of $\sim 8 \times 10^{39} \text{ ergs s}^{-1}$, coincident with the position of SN1994W to within $1''.4$. The positional coincidence plus the optical evidence for a dense circumstellar shell support the identification of the X-ray source as SN1994W.

Subject headings: stars: supernovae: individual (SN1994W) — galaxies: spiral — X-rays: galaxies

1. Introduction

X-ray emission from supernovae arises either from Compton-scattered γ rays from the radioactive decay of ^{56}Co or from the interaction of the circumstellar matter with the supernova's shock wave. For the case of circumstellar interaction, X-rays provide a view of the last years of the progenitor's life, specifically, the years of mass loss. Supernovae undergoing circumstellar interaction are expected to emit X-rays with energies from 1 keV to 100 keV (Chevalier & Fransson 1994). The recently-recognized hypernovae class, supernovae which show evidence of extreme blast wave energies ($\sim 10^{52} \text{ ergs s}^{-1}$) (Wang 1999; Fryer & Woosley 1998; Paczyński 1998) and association with GRBs, also contribute X-ray emission.

Currently, nine "normal" supernovae have been detected in the X-ray band: SN1978K, SN1979C, SN1980K, SN1986J, SN1987A, SN1988Z, SN1993J, SN1994I, and SN1995N (Schlegel (1995) and references therein for supernovae earlier than 1994; Lewin et al. (1995) for SN1995N; Immler, Pietsch, & Aschenbach (1998a) for SN1979C and Immler, Pietsch, & Aschenbach (1998b) for SN1994I). Of these, the early X-ray emission from one (SN1987A) largely arose from Compton-scattered γ -rays from the radioactive decay of ^{56}Co . The emission from the other eight is believed to come from the interaction of the SN shock with a cir-

cumstellar medium (the currently increasing late X-ray emission from SN1987A also comes from the shock interaction (Hasinger, Aschenbach, & Trümper 1996)). A tenth supernova, SN1998bw, identified as a possible hypernova and perhaps associated with GRB980425, has been detected in X-rays (Pian et al. 1998).

This paper describes the detection of X-ray emission from the location of SN1994W.

2. Summary of Discovery

SN1994W in NGC 4041 was discovered by G. Cortini and M. Villi on 1994 July 29.85 (Cortini & Villi 1994). The supernova was located approximately $17''.5$ N and $7''.8$ W of the nucleus of NGC 4041 (Pollas 1994). Bragaglia, Munari, & Barbon (1994) obtained a spectrum using the Bologna Astronomical Observatory 1.5-m that showed a flat continuum with strong $\text{H}\alpha$ and $\text{H}\beta$ emission lines defining SN1994W as an SN II. No P Cygni profiles were observed in the first spectrum. Filippenko & Barth (1994) reported that a spectrum obtained with the Lick Observatory 3-m confirmed SN1994W as a peculiar SN II. The emission lines showed a narrow component (FWHM $\sim 1200 \text{ km s}^{-1}$) sitting on a broad base (FWHM $\sim 5000 \text{ km s}^{-1}$). Narrow Fe II emission lines were detected. Narrow absorption components were visible in the cores of the emission lines with FWHM

$\sim 300 \text{ km s}^{-1}$. Subsequent spectroscopy showed narrow (FWHM $\sim 1200 \text{ km s}^{-1}$) P Cygni profiles. Cumming, Lundqvist, & Meikle (1994) described a spectrum obtained about two weeks later that showed little change in the emission lines. They suggested that the lack of change implied the supernova illuminated a dense circumstellar shell. Radio and X-ray emission could be expected.

3. X-ray Observation

The *ROSATHRI* was used to observe SN1994W on 21-23 October 1997 for an on-source time of 33.7 ksec. The MJD of the middle of the observation is 50742.04. The original processing of the data contained a $10''$ boresight error, so the data were re-processed after a patch was applied to fix the pipeline software. Sollerman, Cumming, & Lundqvist (1998) (hereafter, SCL98) established the date of outburst as 1994 July 14^{+2}_{-4} so the HRI observation date corresponds approximately to an age of 1180 days.

The particle background of the data was removed using the software described by Snowden (1998). The deadtime-corrected exposure totaled 33460.8 sec. The HRI data were binned to $4''$ pixels and registered with an optical image from the Digitized Sky Survey 2 atlas¹. The binned data were then overlaid on the optical image. No smoothing was applied to the X-ray data. Figure 1 shows the results with X-ray contours over an optical image.

A point source at the position of SN1994W is visible in the figure. At the position of the X-ray source, the contours are 2.5, 3.0, and 3.5 counts pixel^{-1} . The 2.5 counts pixel^{-1} contour is 2-3 times the background rate. The coordinates of the X-ray source are 12:02:11.0, +62:08:31.7 (J2000) while the coordinates for SN1994W are 12:02:10.9, +62:08:32.6. The differences, defined as X-ray minus optical, are $+0^s.1$ in RA and $-0''.9$ in Dec. To check the positional accuracy, the coordinates of the nucleus of NGC 4041 were extracted and compared to published values (Russell et al. 1990; Polas 1994). The differences (X-ray minus published) are $+0^s.1$ in RA and $+1''.1$ in Dec. The absolute position of SN1994W is accurate to $\sim 1''.4$, a value well within the pointing error of the HRI ($\sim 6''$).

A net total of 31 ± 7.3 counts was extracted from a $3''$ radius circle centered on SN1994W's position. These counts correspond to a net source rate of $9.3 \pm 2.2 \times 10^{-4} \text{ counts s}^{-1}$. The extraction circle contained 50% of the PSF, so the count rate must be increased by a factor of 2. The background that was subtracted was obtained from an annulus surrounding the galaxy that had an inner radius of $1'$ and an outer radius of $2'$.

The probability of a source falling at the exact location of SN1994W will be given by the probability of a random background fluctuation at that location, an estimate based on the log N-log S for the measured flux, or approximately by the number of sources detected in the galaxy divided by the galaxy area. This last number will be the larger of the three. For example, from a *ROSAT*-measured log N-log S relation (e.g., Hasinger, Schmidt, & Trümper (1991)), one source, of flux $\sim 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$, is expected per square degree (i.e., a probability of $\sim 2 \times 10^{-6}$ for the detect cell used here). Figure 1 shows at least 4 sources at or above that flux. The D_{25} radius of the galaxy is $\sim 2'.7$ (Tully 1988). If we exclude the $\sim 8''$ nuclear region, the resulting annulus has an area of $\sim 7.5 \times 10^4 \text{ arcsec}^2$ in which about 8-10 sources are located. This gives a probability of $\sim 10^{-4}$ per arcsec^2 ; multiplying by the size of the detect cell gives a probability of $\sim 3 \times 10^{-3}$ of a source falling precisely on the SN1994W position. We judge this to be sufficiently small to associate SN1994W with the X-ray source on a provisional basis.

The Galactic reddening in the direction of NGC 4041 is $E_{B-V} \sim 0.017$ (Schlegel, Finkbeiner, & Davis 1998) which converts to $N_H \sim 9 \times 10^{19} \text{ cm}^{-2}$ using the conversion of (Predehl & Schmitt 1995). However, SCL98 estimate a value for E_{B-V} of 0.17 ± 0.06 from the interstellar Na I D absorption line using the calibration of Munari & Zwitter (1997). That E_{B-V} converts to a column density of $\sim 9 \times 10^{20} \text{ cm}^{-2}$. We adopt the higher column because SCL98 detected the Na I line directly toward SN1994W. The difference between the Galactic and the Na I-determined values for E_{B-V} is a measure of the absorption local to the SN1994W region. Using an assumed thermal bremsstrahlung spectrum with $kT \sim 5 \text{ keV}$, the count rate converts to an unabsorbed flux in the 0.1-2.4 keV *ROSAT* band of $\sim 1.1 \pm 0.3 \times 10^{-13} \text{ ergs s}^{-1} \text{ cm}^{-2}$. Using a distance of 25.4 Mpc (SCL98),

¹Image obtained from <http://archive.eso.org/dss/>

the L_X is $8.5 \pm 2.0 \times 10^{39}$ ergs s^{-1} .

4. Discussion

The positional coincidence and the optical spectral behavior argue that SN1994W has been detected in the X-ray band. The detection of narrow absorption lines in the optical spectra requires the existence of a dense circumstellar shell. SCL98 estimate a number density for the shell of $>10^8$ cm^{-3} from the presence of optically thick Fe II lines. The estimated X-ray luminosity is comparable to that of SN1986J, SN1988Z, and SN1995N (Schlegel 1995) and lies near the upper end of the X-ray luminosity range for supernovae.

No other X-ray observations have been made of NGC 4041. The IRAS observation of NGC 4041 had, at the best spatial resolution, a beam size of $0'.77$ which provides essentially no spatial information (Soifer et al. 1989). A VLA image at 4.85 GHz was obtained at $1'$, again providing no spatial information (Becker, White, Edwards 1991). Certainty that SN1994W has been detected in the X-ray band will only be possible with additional observations, particularly with *Chandra*. The X-ray light curve, whether increasing or decreasing, is of interest.

Table 1 lists parameters generated from the competing models of Chevalier & Fransson (1994) (hereafter, CF94), which applies to normal Type II supernovae exploding into a red giant wind, and Terlevich et al. (1992) (hereafter, the ‘cSNR’ model), which describes a supernova expanding into a very dense circumstellar environment (equations summarized in Aretxaga et al. (1999)). The parameters for the CF94 model are calculated for two different values of the power law index n that describes the expanding gas. Each model is calculated for two different ages, at a template value of 30 days and at the age of the *ROSAT* observation. For the number density, we adopt the lower bound of 3×10^8 cm^{-3} (SCL98).

Both models show similar behavior: temperatures and velocities decrease from day 30 to day 1180 and shell radii and luminosities increase. In detail, however, the models differ. The initial velocities of the CF94 $n = 7$ models are too high; the observed FWZI velocities near day 30 were ~ 5000 $km\ s^{-1}$. For the $n = 20$ model, the initial velocity is correct, but the day 1180 velocity remains

too high and the X-ray luminosity is too low. The cSNR model appears to be a better match to the observations. The luminosities in the cSNR model are too large by factors of 100-1000, but we have little or no information for the efficiency of the X-ray production. An efficiency value of ~ 0.1 -1% would bring the prediction into line with the observation. Optically, SN1994W showed P Cygni profiles at $H\alpha$ and, for the first 100 days, showed a Type IIP light curve (SCL98). The spectrum also resembled the spectra of Type IIn supernovae such as SN1988Z and SN1987B (Filippenko 1997; Schlegel 1990; Schlegel et al. 1996). On the basis of its optical behavior, SN1994W may fall near the middle of a continuum that has at one extreme the IIn supernovae, with dense circumstellar shells, and at the other extreme “normal” Type II supernovae with little or no circumstellar medium. The X-ray behavior, however, places SN1994W among the most luminous IIn supernovae (assuming that the distance to NGC 4041 is known accurately).

We note in passing that the face-on spiral galaxy NGC 4041 is itself of interest. At least six point sources have been positively detected in the HRI image; another six may exist near the nucleus. The nuclear emission appears to be extended, although the emission may be the blended emission of nearby point sources. The X-ray study of this galaxy will benefit from an observation with *Chandra*.

In summary, an observation of NGC 4041 with the *ROSAT* HRI has revealed the existence of an X-ray source at the position of SN1994W. The signature of a dense circumstellar shell in the optical spectrum plus the positional coincidence of the X-ray source with the optical position support the identification of the X-ray source as SN1994W, the eleventh supernova discovered to emit X-rays.

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TABLE 1
COMPARISON OF MODEL QUANTITIES^a

Quantity	cSNR models		CF94 models			
			n = 7		n = 20	
	30 d	1180 d	30 d	1180 d	30 d	1180 d
R_s (cm)	6.9(15)	1.9(16)	7.7(15)	1.4(17)	1.7(15)	5.6(16)
V_s (km s ⁻¹)	7880	570	31800	15300	7780	6330
T_s (K)	8.8(8)	4.6(6)	5.0(8)	1.2(8)	1.9(6)	1.3(6)
T_s (keV)	80	0.42	45	11	0.17	0.12
L_s (ergs s ⁻¹)	1.5(44)	4.7(41)	2.9(41)	3.2(40)	1.9(39)	1.0(39)
M_{shell} (M_\odot)	0.37	8.6	2.0(-4)	3.7(-3)	4.3(-5)	1.4(-3)

^aValues in parentheses are exponents

NOTE.—The adopted quantities applied to both models are as follows: explosion energy = 1.3×10^{51} ergs s⁻¹; number density of 3×10^8 cm⁻³ as a lower limit (SCL98). For the CF94 models, the adopted mass loss rate is $10^{-5} M_\odot$ yr⁻¹ and a wind velocity of 10 km s⁻¹. The cSNR model yields a time t_{sg} for the onset of radiative cooling of 18.5 days.

Fig. 1.— *ROSAT* HRI contours on a DSS2 optical image of NGC 4041. The X-ray data were binned to 4'' pixels before registration. No smoothing was applied to the HRI data before contouring which explains a few of the “linear” features in the contours. Contours were drawn at 2.5, 3.0, 3.5, 4.0, 5.0, 7.5, 10.0, 12.5, 15.0, and 20.0 counts pixel⁻¹. The contour at 2.5 counts pixel⁻¹ is a factor of 2-3 above the background. The white ‘+’ marks the optical position of SN1994W.

